Numerical Simulation of Blade Vortex Interaction (BVI) In Helicopter Using Large Eddy Simulation (LES) Method

John Sherjy Syriac and Narayanan Vinod

Abstract In this paper, computational fluid dynamics (CFD) viscous flow simulation of BO-105 isolated helicopter rotor blades was simulated using commercially available STAR-CCM + software. The aim of these simulations is to capture the complex flow dynamics and blade vortex interaction (BVI) noise generation in hover configuration. In order to capture the complex nature of BVI and viscous wake precisely and accurately, large eddy simulation (LES) method was used. Overset mesh was used as mesh technique. The mesh technique and number of cells play an important role in capturing this complex phenomenon. Computational aero-acoustics (CAA) method was used to capture the noise generated due to the rotation of rotor blades. Ffowcs-Williams–Hawkings unsteady equation formulation was used to capture the far-field acoustics. Both CFD and CAA together helped to obtain the flow dynamics as well as far-field noise generated. The hover performance parameters obtained from numerical simulation showed good agreement with the theoretical and experimental data. The frequency spectral analysis of the acoustical data showed number of peaks that correspond to blade passage frequency (BPF) and its harmonics. The sound pressure level SPL of receivers at $\sqrt{2}$m in Cartesian coordinates at 45° elevation in 1st and 4th quadrants was greater compared to that of rotor plane receivers. The maximum SPL of 121 dB was measured by receiver directly below the rotor hub of the helicopter.

Keywords Blade vortex interaction · Computational fluid dynamics · Computational aero-acoustics · FW-H equation · STAR-CCM+

J. S. Syriac · N. Vinod (✉)
Department of Mechanical Engineering, IIT Gandhinagar, Palaj, Gandhinagar, Gujarat, India 382355
e-mail: john.sherjy@iitgn.ac.in

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1 Introduction

The dependence on helicopter and rotorcrafts for various missions is increasing in recent times. The peculiar nature of rotorcraft operation makes it special compared to other fixed-wing rotorcrafts. This makes it useful for various operations which are not possible by fixed-wing aircraft. The increase in rotorcraft operations causes an adverse effect on noise generation.

The flow field around the helicopter signalises a complex physics which involves three-dimensional flow nature, high level of unsteadiness, complex trailing and tip vortices [1]. This intricate nature of the flow makes the analysis of helicopter aero-dynamics an extremely challenging task. The genesis of tip vortices formed at the tip of the blades is due to pressure difference occurring above and below of the blade. This results in curling of air from the bottom blade surface towards the top surface which leads to strong vortex formation. The vortex strength depends on various factors such as the core radius and vortex distortion. These strong vortices interact with the succeeding blade which results in sudden large unsteady pressure fluctuations on the blade surface. This phenomenon is called blade vortex interaction (BVI). The vortical wake has a strong impact on the helicopter performance in both hover and forward flight conditions.

Rapid advancement in both experimental and computational code in the recent years has led to deeper understanding of the noise generating mechanisms in the helicopter. There are different noise sources that are present in the helicopter like loading noise, thickness noise, High-speed impulsive noise, BVI noise, engine noise, trailing edge noise, broadband noise and minor noises which can be seen in Fig. 1. BVI noise is one of the main contributors to the overall helicopter noise level produced. The downwash nature of the tip vortices causes a downward force on the rotor blade at the tip region which results in the decrease in the force as well as an increase in intense noise. The large unsteady pressure fluctuation mainly occurs near the leading edge of the airfoil. BVI noise has a distinct directivity pattern which is mainly forward and below the rotor plane. The above stated points are the striking features of BVI noise [2]. Following are the parameters which affects the BVI noise: (1) advance ratio, (2) tip-path-plane angle, (3) advance tip Mach number and (4) intersection angle between the blade and vortex centre [3]. The present-day helicopters are still noisy and have lots of aero-mechanical vibrations inspite of the use of modern technologies which poses as a disturbance to the public. Government regulations, noise reduction policy and public acceptance demand a reduction in BVI noise. The continuous increase in the number of helicopters has thus made it mandatory to control and reduce the increased noise generated by them.

The advancement of computational numerical methods and high-performance computing facility over the recent years has made numerical aero-acoustics simulations feasible and practical. Computational aero-acoustics (CAA) is a branch of aero-acoustics where noise generated due to turbulent flow is evaluated through various advanced numerical methods and techniques. At present, coupling of both

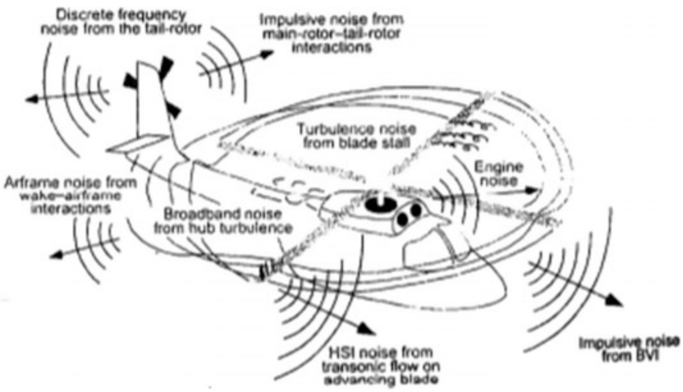

Fig. 1 Various noise generation mechanisms in a helicopter

computational fluid dynamics and computational aero-acoustics has been used as a numerical tool for deeper understanding of the complex three-dimensional unsteady flow and various noise generating mechanisms of helicopter and other rotorcrafts.

When the helicopter is moving forward with an advance ratio, the advancing side experiences a higher relative velocity as the rotational speed of the rotor blade adds with the forward velocity ($V_a = V + R\Omega$) than on the retreating side which experiences lesser relative velocity as the rotational speed gets subtracted with the forward velocity ($V_r = V - R\Omega$). Due to this difference in velocities on both sides of the rotor blade regions, it results in unsymmetrical lift distribution on the rotor blades. Cyclic and longitudinal pitch controls are used to control the lift distribution on the rotor blades. In the case of hover condition, there is symmetrical flow pattern in both regions leading to symmetrical lift distribution which is of concern in this paper.

Various theoretical approaches [5, 6, 12] and experimental tests have been carried out on BO-105 helicopter in DNW tunnel [7] at different advance ratio to capture the acoustic data for BVI noise. There are various theories which include moment theory, blade element theory to determine the helicopter performance like thrust coefficient, power coefficient, etc. Widnall [8], Lowson and Ollerhead [9] were the people to study the BVI noise generation through theoretical prediction. Ffowcs Williams and Hawkings formulated the FW-H equation [10] which is used for sound generation due to motion of the noise source. FW-H equation is the most generalised form of Lighthill's analogy which is a non-homogenous wave equation that includes both volumetric and surface source terms. Farassat et al. [11] used the FW-H equation in the form of surface and volumetric integrals to calculate the far-field pressure noise. The integral equation consists of two terms—surface and volumetric terms. The thickness (monopole) surface term denotes the noise generation as a result of displacement of fluid particles due to the presence of body motion. The loading (dipole) surface term denotes the noise generation as a result of variation of force distribution on the body surface due to body motion. The

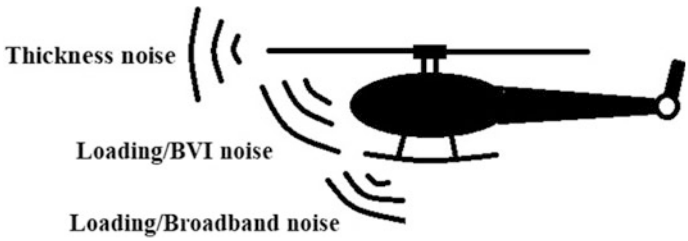

Fig. 2 Schematic picture of radiated directive pattern of noise source

volumetric (quadrupole) source term denotes noise generation as a result of non-linear flow characteristics due to change in local speed of sound and velocity of fluid near the blade surface. The directivity pattern of noise sources [12] can be seen in Fig. 2. Recent theoretical work of Martin Lowson [13] showed the BVI location points and prediction of noise on the rotor disc.

Computational aero-acoustics simulations have not been widely done due to its complexity and limitations in computational resources. Accurate noise prediction is a difficult challenge which has not yet been accomplished due to the complex nature of vortex interaction and full physics of the interaction has not yet been completely understood. Resolution of very small vortices requires very fine mesh elements which in turn increases the computational time and resources. Hence, the availability of resources limits the mesh quality. Large eddy simulation is a promising numerical method to solve complex turbulent flow at high Reynolds number. Direct numerical simulation (DNS) can resolve very small eddies but requires high computational resources and simulation time. Hence, the use of DNS for 3D complex flow is not practical and is time-consuming. LES captures sufficiently small eddies from fluctuating flow and requires lesser resources compared to DNS which makes it feasible to simulate complex flow [14]. LES method can be used to find acoustic source terms in simulation and far-field noise can be calculated by various CAA analogies. Hence, LES with CAA analogies is a promising numerical method to simulate turbulent flows and study far-field noise propagation. In this paper, aero-acoustics of isolated rotor blade in hover configuration has been simulated.

2 Computational Methodology

Solidworks 2016 was used for modelling geometrically half scaled isolated HART II BO-105 helicopter rotor blade configuration which is shown in Fig. 3 whose specifications are shown in Table 1. The model consists of four bladed rigid rotors with linear twist angle θ and no coning angle. Swashplate is not included in the model to avoid complexity of the model.

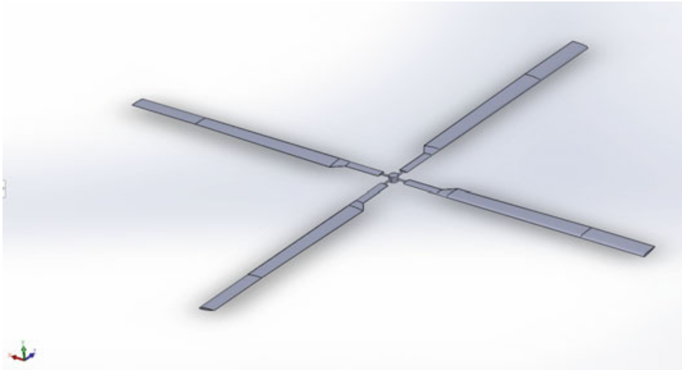

Fig. 3 Isolated rotor blade model in hover configuration

Table 1 Geometric specification of the model

Geometry	Dimension
Airfoil section	NACA 23012
No of blades (*N*)	4
Rotor radius (*R*)	1 m
Chord length (*c*)	0.0605 m
Root cut off	0.22 R
Zero twist radius	0.75 R
Linear twist θ	−8° upto 75% R
Scale factor (γ)	4.91
Solidity (σ)	0.077
Collective angle θ_1 @ 0.75 R	−2°, 2°, 6°, 10°
Rotor rpm	2086 rpm
Tip Mach number M_{tip}	0.6291

Commercial software STAR-CCM+ was used to examine the flow dynamics and BVI noise of rotor blade in hover configuration. The hover performance was evaluated by varying the collective angle of the blade. Unsteady RANS k-omega model and LES was used to evaluate the performance of the helicopter due to limited availability of computational resources. The computational domain is a closed cuboidal domain resembling a wind tunnel test setup which is shown in Fig. 4. The domain specification is shown in Table 2. Computational domain is sufficiently large to avoid end wall boundary effects. Overset mesh was used as meshing technique which can be seen in Fig. 5. In this technique, the entire domain is divided into two regions—background region and inner region—which is confined around the rotor blade and is cut from the background region and the data are transferred between the inner mesh and background mesh through interface region. Inner cylindrical region is rotated at a specific rpm. Blade flapping and cyclic

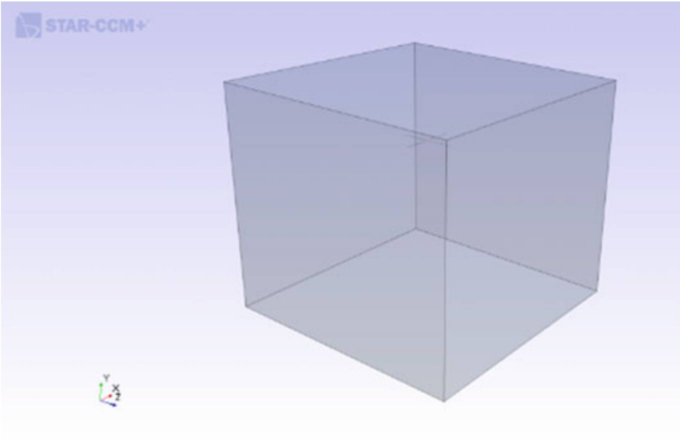

Fig. 4 Geometry scene of rotor model in STAR-CCM+

pitching have not been taken into consideration in this simulation for simplicity of the problem.

To study the BVI noise, collective angle of 2° case was taken into consideration. In order to accurately capture the complex nature of tip and shed vortices, LES method was used. The accuracy of noise captured highly depends on the mesh quality. Finer the mesh elements, the better will be the noise captured. Due to computational limitations, mesh elements were limited. In this study, far-field noise was captured by Farassat formulation of unsteady FW-H equation. The FW-receivers were kept at specific locations to capture the unsteady acoustic pressure fluctuations. Four receivers (1–4) were kept at a radius of 2R 90° to each other in the plane of the rotor and two receivers (5, 6) at $\sqrt{2}$ Cartesian coordinates in the 1st and 4th quadrants at an elevation angle 45°. Five receivers (7–11) were arranged as an array 1.1R below the rotor hub. Spectral frequency analysis was done by fast Fourier transform (FFT) of the acoustic pressure data from the receivers to obtain the sound pressure level (SPL) (dB) of individual tonal components.

Table 2 Computational domain specification

Boundary	Boundary condition	Dimension (m)
Inlet	Wall slip	4.5
Outlet	Wall slip	4.5
Left	Wall slip	4.5
Right	Wall slip	4.5
Top	Wall slip	2
Bottom	Wall slip	6
Rotor	No-slip	–

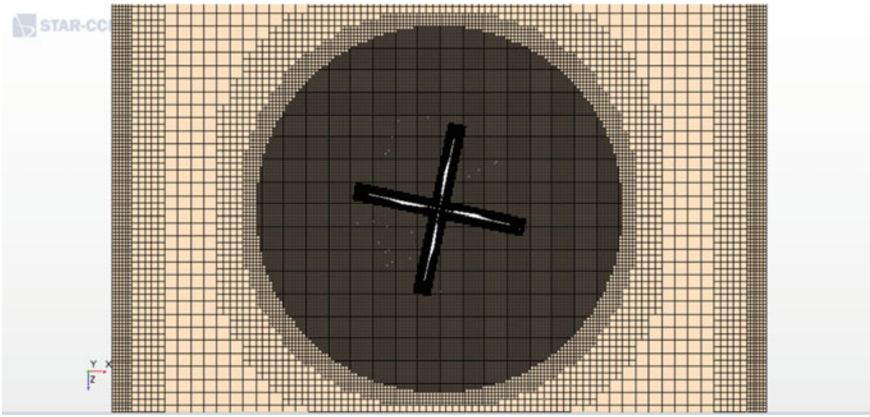

Fig. 5 Overset mesh technique

3 Result

This section is structured as follows. In the first half, results of hover performance and figure of merit of BO-105 helicopter rotor are discussed. In the second half, results of acoustical data of 2° collective angle case are discussed to analyse the BVI noise. Acoustical data from microphone receivers are analysed to obtain the sound pressure level due to BVI interaction.

3.1 Hover Performance Validation

The hover performance characteristics of isolated helicopter rotor were obtained from STAR-CCM+ with details already mentioned in the above section. Various non-dimensional aero-dynamic parameters (force coefficient, power coefficient and figure of merit) were computed to tabulate the hover performance of the helicopter. RANS and LES of the rotor at various collective angles were simulated and validated with the available experimental and theoretical data. Velocity distribution varies along the blade with minimum at the inboard of the rotor to maximum at the rotor tip which can be clearly seen from Fig. 6. Hence, the lift varies from inboard to outboard of the rotor. Axisymmetric velocity distribution can be seen in hover from the figure as each blade experiences same tip velocity and periodic flow environment. The pressure on the surface of the blades is shown in Fig. 7 for the 2° collective angle case. From the figure, it can be seen that pressure on the lower surface is greater than the upper surface. Pressure difference on both sides of the surface leads to positive lift of the rotor upwards. The tip vortices generated from the blade rolls up into concentrated vortices and travels downstream. These vortices interact with the succeeding blade resulting in unsteady pressure fluctuation on the blade surface which causes BVI noise. Figure 8 shows the trajectory of the tip vortex in 6° collective angle case. Due to rotation of the rotor, air is sucked into the plane of the rotor causing an inflow into the rotor plane and the tip vortices travel downwards passed the rotor in a cycloidal pattern which can be easily seen from the figure.

Figure 9 shows the pressure fluctuation waveform due to aerodynamic interaction between the blade and tip vortices of the preceding blade. The lift of the rotor is affected by these interactions. The flow field gets altered frequently due to the formation of tip vortices which causes sudden unsteady pressure fluctuation on the blade surface during interaction which in return causes aero-acoustical noise called BVI noise.

Hover performance and Figure of merit plot of the isolated rotor in hover configuration for 3 revolutions is shown in Figs. 10 and 11 as thrust of the rotor was varied by changing the collective angle of the rotor. The obtained values from simulation were plotted against experimental data and theoretical prediction of thrust and power coefficient from simple momentum theory. Measured values from the simulation are in good agreement with the experimental data and momentum theory.

3.2 *Aero-Acoustical Analysis*

LES simulation has been carried out for 2° collective angle in this case. Farassat 1A integral formulation was used to capture far-field acoustics by FW-H receivers whose locations are mentioned in the above section. Sound pressure level in dB was obtained by fast Fourier transform of the captured pressure data. The reference pressure used for the simulation is $P_{ref} = 2 \times 10^5$ Pa. Figures 12 and 13 show the spectrum of SPL data of various receivers. The plot shows a number of peak

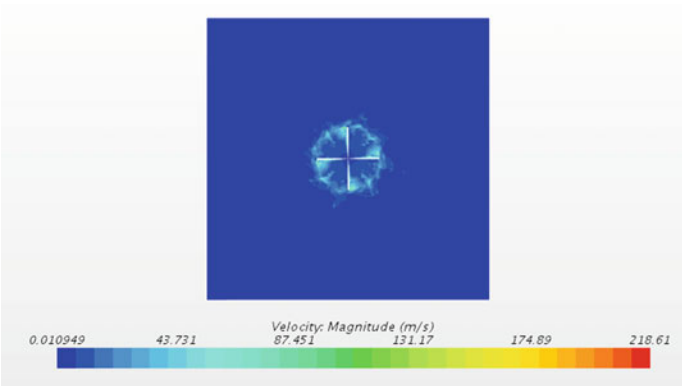

Fig. 6 Velocity scalar scene at section plane of rotor

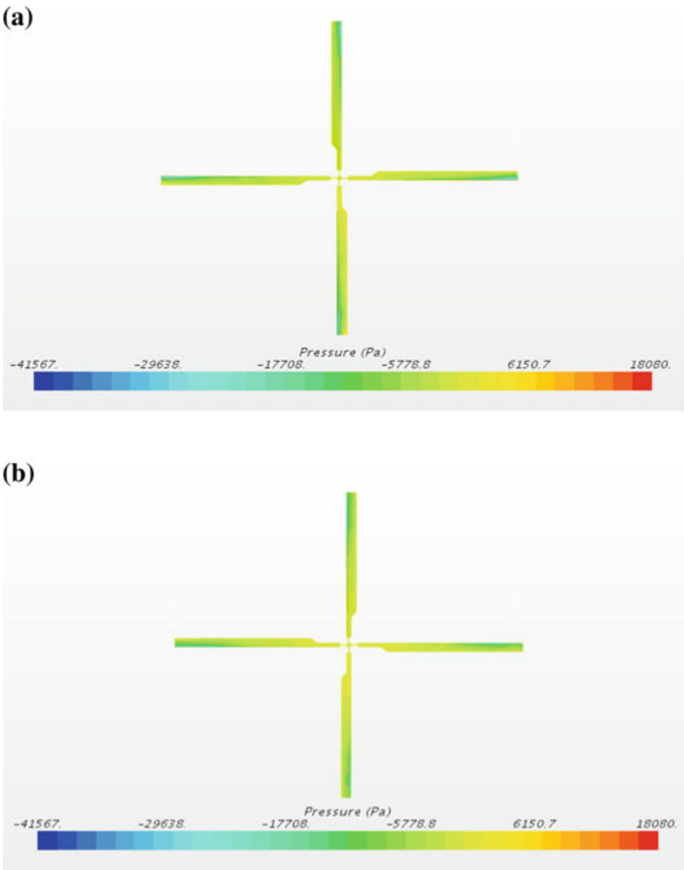

Fig. 7 Pressure distribution on blade surface, **a** upper surface, **b** lower surface

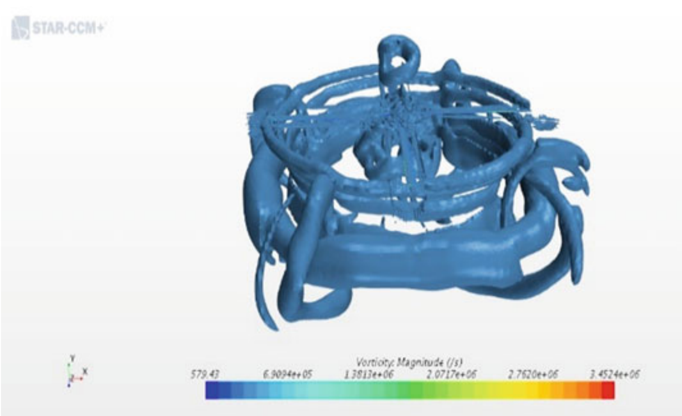

Fig. 8 BO-105 rotor Q-criterion (2000/s^2)

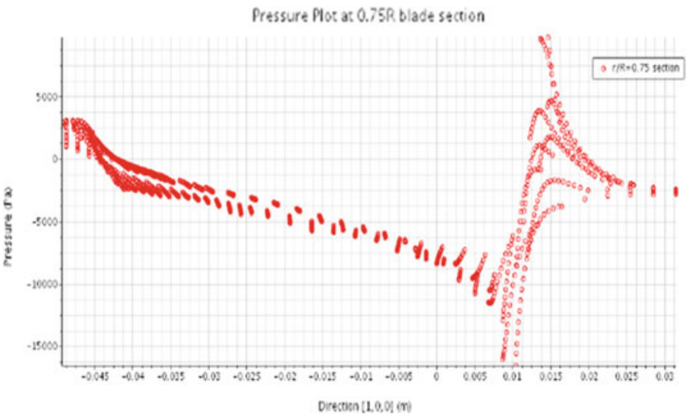

Fig. 9 Pressure distribution around the blade surface

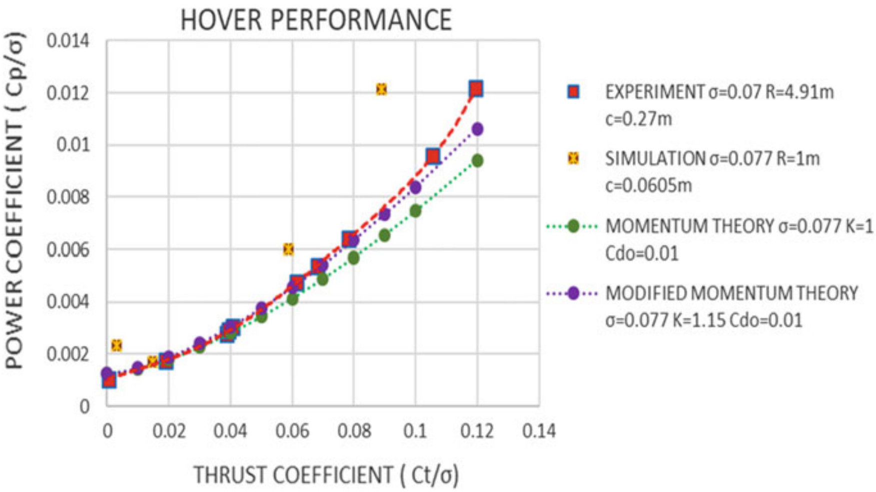

Fig. 10 Hover performance plot of BO-105 isolated rotor

pressure values ranging from low frequency to high frequency. Noise captured by the receivers is a combination of various tonal components of many frequencies. Peaks of different magnitude of tonal components correspond to blade passage frequency (BPF) which is fundamental frequency and its harmonics at lower-mid frequencies. Broadband noise can be seen at higher frequencies. It is observed that the SPL of receiver 5 and 6 with receiver 5 higher than receiver 6 by 1 dB was higher compared to those in the rotor plane. Hence the BVI noise was highest at 45° elevations than in the rotor plane indicating that BVI noise propagates in-plane as well below the rotor plane. The accuracy of captured noise increases with mesh quality. Overset interface interpolation introduces errors which affect the far-field

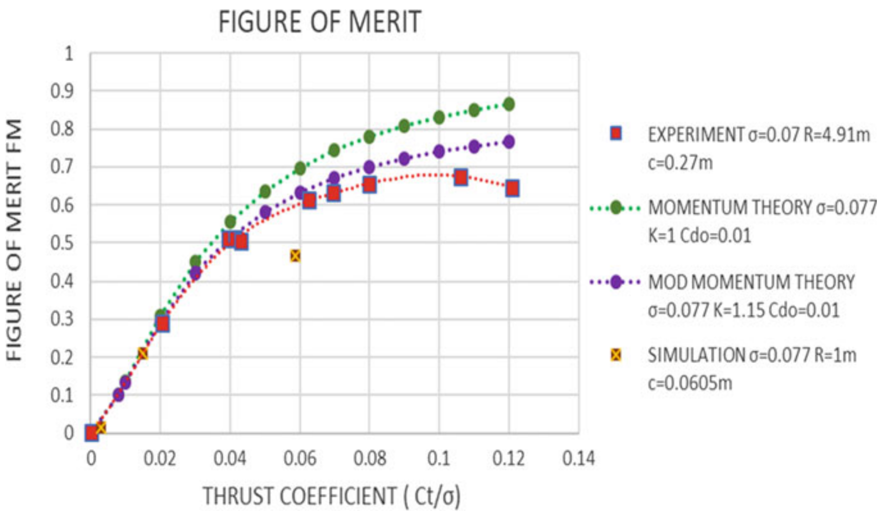

Fig. 11 Figure of merit plot of BO-105 isolated rotor

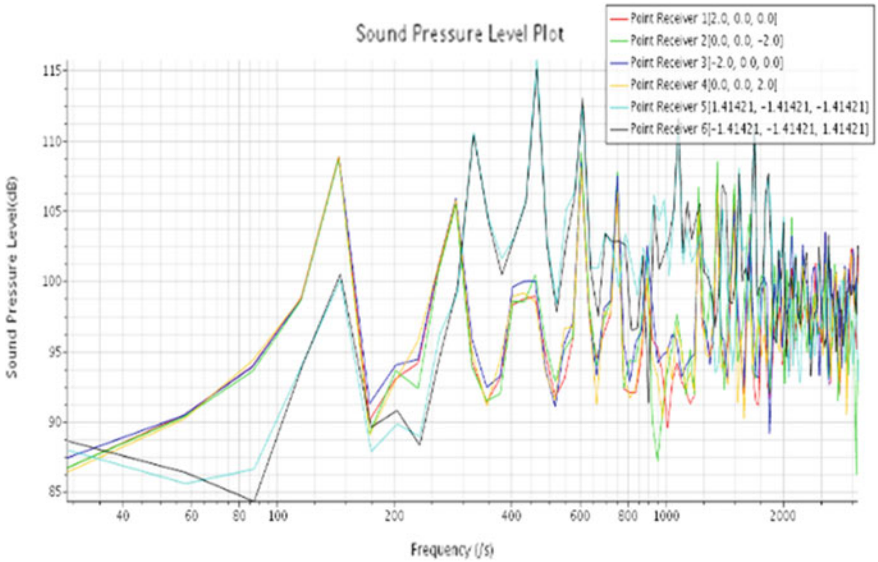

Fig. 12 Sound pressure spectra of 6 receivers in-plane of rotor and 45^0 deg elevation

pressure propagation. The maximum SPL of 121 dB was observed by receiver 9 directly under the rotor hub. Increase in number of FW-H receivers locations by varying elevation and azimuthal angles will help to study the BVI noise propagation in detail.

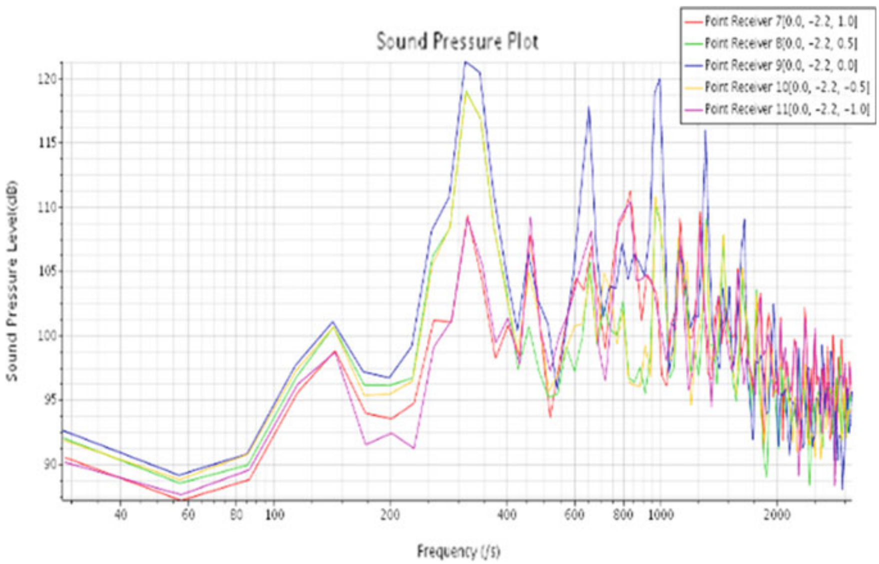

Fig. 13 Sound pressure spectra of 5 receivers array

4 Conclusions

In this paper, numerical aero-acoustical simulation of HART II rotor has been successfully simulated by commercial software STAR-CCM+ using unstructured meshes. overset mesh was used as meshing technique. Aerodynamic coefficients and helicopter performance were tabulated and compared with existing experimental and theoretical data. Obtained values show good agreement with the available data. At higher collective angles, aero-dynamic values deviated more from the experimental data. Mesh quality plays an important role in capturing small complex vortex structures. The finer mesh would produce more accurate results. Availability of computational resources limits the computational accuracy and time.

Aero-acoustics analysis was carried out by LES and CAA analogies. LES method was used to accurately capture the small-scale vortices to study the BVI noise. Farassat formulation of FW-H equation was used to obtain far-field pressure fluctuations. Frequency analysis was done by taking fast Fourier transform of the receiver data to obtain the sound pressure level SPL (dB) plot. The plot showed a number of peaks signifying Blade passage frequency and its harmonics. BVI noise was seen to be propagated in-plane and below the rotor plane. It was observed that the SPL of the noise at 45° elevation was higher compared to SPL of receivers in-plane of the rotor.

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Future Work In the near future, in order to capture the wake accurately and its effect on lift, LES method will be used for the same. Detailed analysis of BVI noise will be done by incorporating more receivers which would deepen the understanding of BVI noise propagation.

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